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Rare-Earth Ions in Niobium-based Devices as a Quantum Memory

Magneto-Optical Effects on Room Temperature Electrical Transport

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ADMINISTRATIVE INFORMATION

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EXECUTIVE SUMMARY

Rare-earth ions are useful for the implementation of quantum memory. In particular, the energy levels and magnetic/spin properties of select ions may enable storage of quantum states. Also, the optical activity may enable optical read-out techniques and optical transmission of qubit states. In addition, the energy levels of ions can be used for designing superconducting qubits where the ionic configuration tunes the Hamiltonian for quantum computing. In the more near term, ions embedded in superconductor heterostructure can be used to implement cryogenic memory for superconducting digital computing. Our concept involves embedding rare-earth ions in superconductor devices to provide a low dissipation environment and access to the systems Hamiltonian.

In this report we show results and success in integrating rare-earth neodymium by ion implantation in thin films of niobium and niobium-based heterostructure devices. We model the ion implantation process and confirm the concentration of the nedoymium in niobium by energy dispersive X-ray (EDX) spectroscopy in a scanning electron microscope (SEM). We study the effect of optical illumination and magnetic stimulus on the transport of the devices at room temperature, as it is important to understand the films and devices so they can properly designed and optimized for utility as quantum memory. We find that the magnetic field has a strong effect on the response. We also find that the selectivity in the optical effect when using a broadband halogen lamp in comparison to a light emitting diode (LED) with selectivity in the excitation wavelength, reinforces the role of the magnetic and optically active Nd rare-earth ions on the device response.

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1. INTRODUCTION

Rare-earth ions are useful for the implementation of quantum memory. This technical report presents results of rare-earth neodymium in superconductor films, as it is a potential platform for implantation of quantum memory. Rare-earth ions are useful for the implementation of quantum memory. We recently proposed a novel concept where we use rare-earth ions embedded in thin superconductor films and devices. Rare-earths in oxides have demonstrated relatively long-lasting quantum memory based on several approaches

In particular the energy levels and magnetic/spin properties of select species may enable storage of quantum states. Also, the optical activity may enable optical read-out techniques and optical transmission of qubit states. In addition, the energy levels of ions can be used for designing superconducting qubits where the ionic configuration tunes the Hamiltonian for quantum computing. In the more near term, ions embedded in superconductor heterostructure can be used to implement cryogenic memory for superconducting digital computing.

2. EXPERIMENT

2.1 SAMPLE PREPERATION

Niobium was DC sputtered on Si wafers at 200 W in the presence of Ar. The film thickness was 50 nm. Heterostructure devices were constructed with these configurations, Nb-AlOx-HfOx-AlOx-Nb and Nb-AlOx-HfOx-CrO-AlOx-Nb, with details discussed in [1–2]. The HfOx-only devices were implanted with neodymium. We measure the I-V characteristics at low magnetic field and without broadband Halogen lamp input and an LED selective to 810–850 nm.

2.2 ION IMPLANTATION SIMULATIONS

We use ion implantation as the method of incorporating neodymium in niobium. We made simulations of the ion implantation process using the SUSPRE tool (Figure 1). Our experiment includes several implantation energies and dose to embed neodymium as shown in Figure 2 at different depths, in the top electrode as well as through the barrier between superconductor electrodes. We also implanted control niobium films. The implantations suggest that dose has an effect on the degree of disorder. For 1e13, dose disorder is estimated at less than 20%, whereas with 1e14 at 100%. Ion implants were made by Innovion Inc. with the split of energies and doses. Figure 3 shows the relevant energy levels of neodymium, as well as how these levels are influenced by the superconductor heterostructure device as described in [1–2]. Also shown in Figure 3 are calculations of the dependency of the quantum memory entanglement distance as a function of the quantum memory storage time. Table 1 compares several viable quantum memory technologies and the estimated performance of our ionic:superconductor technology

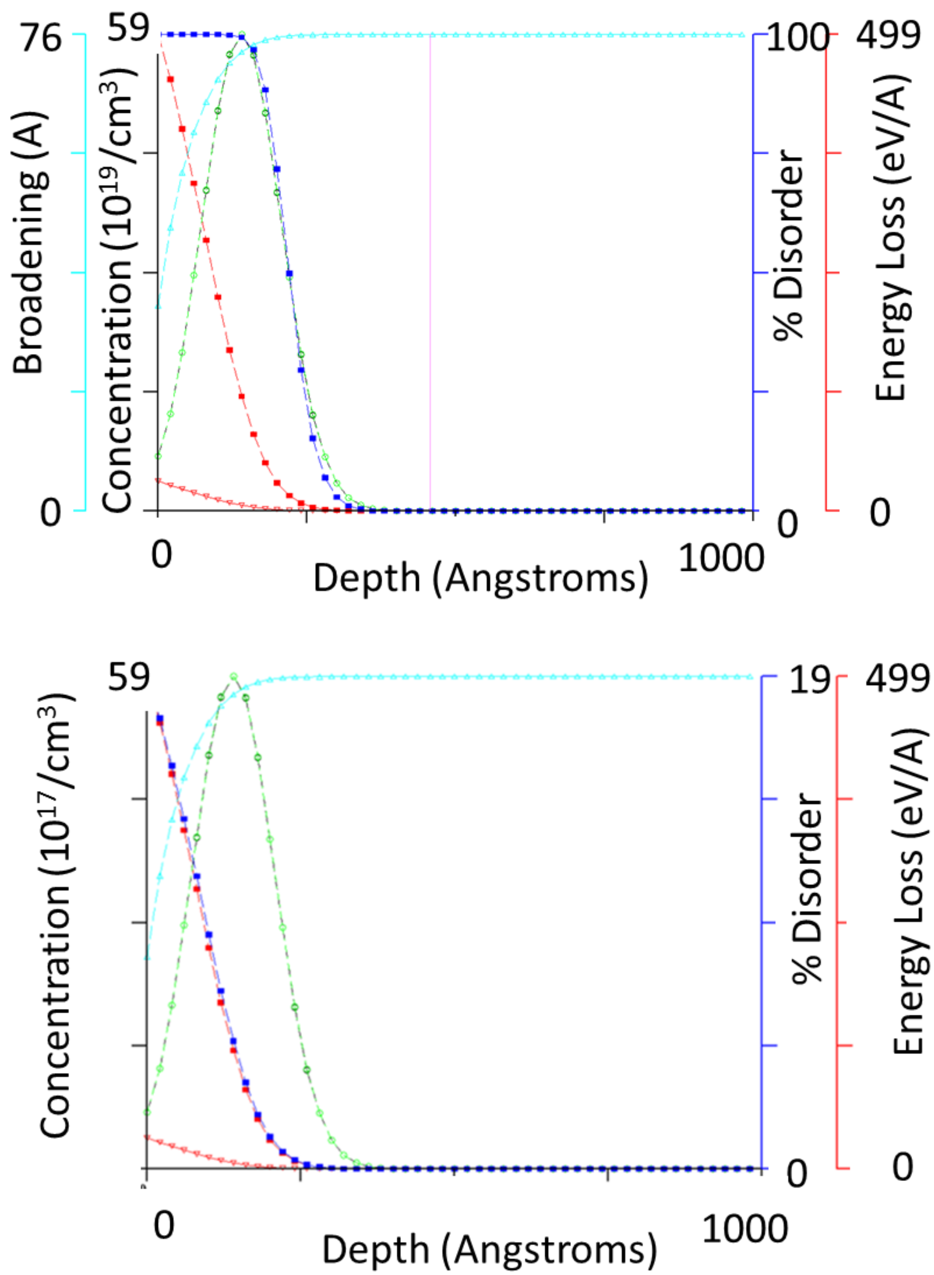


Figure 1. Ion implantation simulations of neodymium in thin films of niobium**.** Simulations are made at low 10^{13}cm^{-2} and high 10^{14} cm^{-2} dose at 60 keV. At high dose, disorder induced is significantly greater and may favor different final arrangement of the ions in the host crystal.

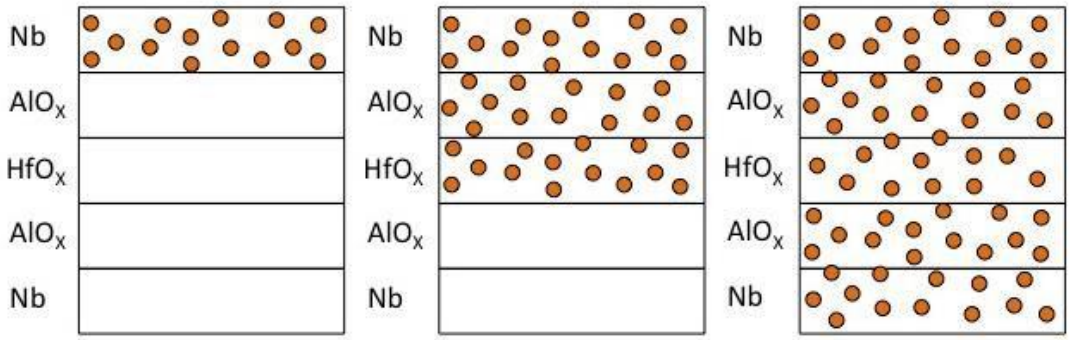


Figure 2. Schematic illustrating the possible arrangements of ions in device hetero-structures, where depending on the implantation energy, the depth penetration of the ions can be controlled.

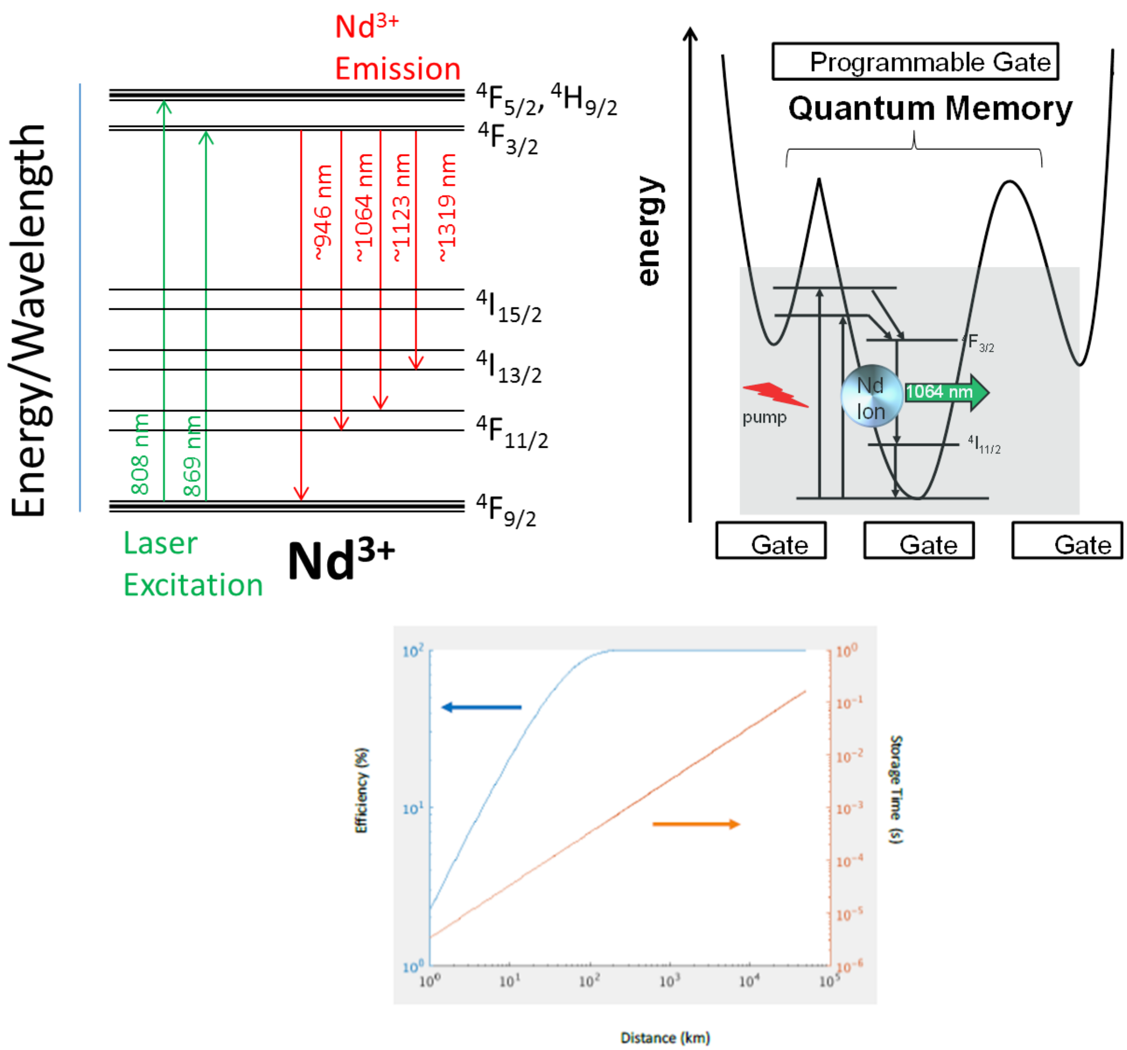


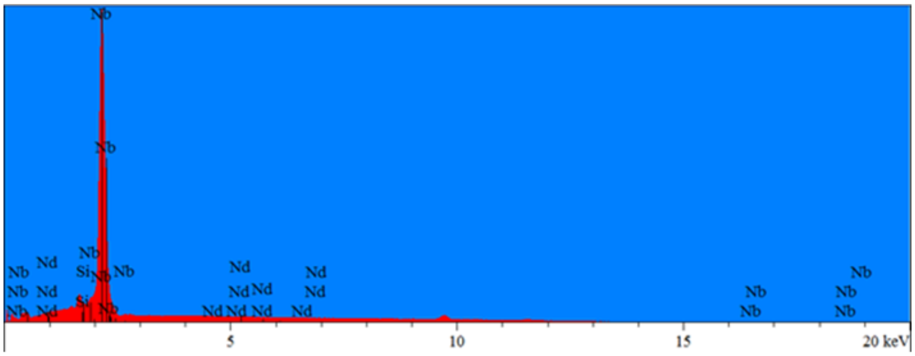
Figure 3. **(a)** Energy level diagram of nedoymium ions showing the excitation and emission wavelengths of known transitions; (b) energy levels when operated in a superconducting device; (c) correlation between entanglement distance and efficiency and storage time of the quantum memories.

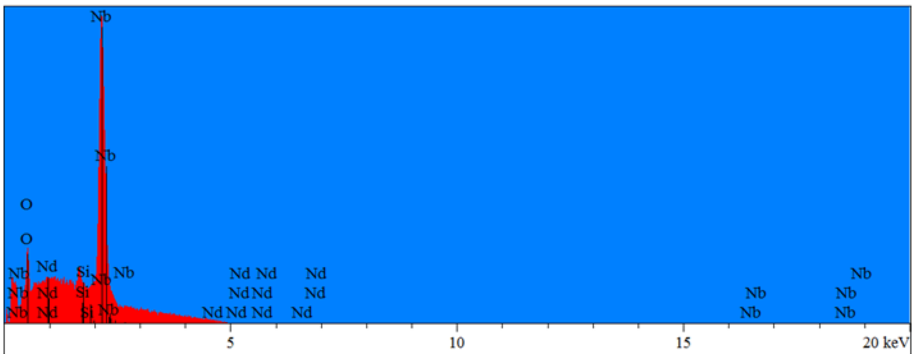
Table 1. Comparison of quantum memory technologies and rare-earth ion in superconductor.

Quantum Memory Technology	Storage/ Coherence Time	Fidelity	Bandwidth	Scalability
This Work Proposed Ionic:Superconductor	**> 1 hour**	>99.99 %	>100 Ghz	<10 nm
Semiconductor	>1 ms	>98%	>1 MHz	<20 nm
Atoms/Ions in gas	> 100 seconds	>99.9%	> 10 MHz	>100 nm
Quantum Dots and Nanotechnology	> 1 milli-second	>99%	>100 MHz	<5 nm

2.3 EDX Spectra

To prove that we have integrated the nedoymium, we examine a thin film sample by EDX spectroscopy in an SEM. The instruments extracted the presence of niobium, nedoymium, silicon and oxygen, which is consistent with the niobium-on-silicon wafer. The instrument detected 1 to 3 % of nedoymium, as shown in the survey scan in Figure 4 and the images in Figure 5, where the bright red spots correspond to detection of the unique signature of neodymium.





Component	Type	Molecular Concentration	Concentration	Units (%)	
O	Calc	13.912	2.751	wt.	
Si	Calc	2.544	0.883	wt.	
Nb	Calc	82.841	95.114	wt.	
Nd	Calc	0.703	1.252	wt.	
		100.000	100.000	wt.	Total

Elt.	Line	Intensity (c/s)	Atomic (%)	Concentration	Units (%)	Error 2-sig	MDL 3-sig	
O	Ka	72.96	13.912	2.751	wt.%	0.074	0.107	
Si	Ka	60.68	2.544	0.883	wt.%	0.037	0.076	
Nb	La	2,399.05	82.841	95.114	wt.%	0.249	0.193	
Nd	La	5.16	0.703	1.252	wt.%	0.280	0.877	
			100.000	100.000	wt.%			Total

Figure 4. EDX spectra with low- and high-dose implant with the detection of Nb and Nd species. Nd concentration is ~1–3% concentration.

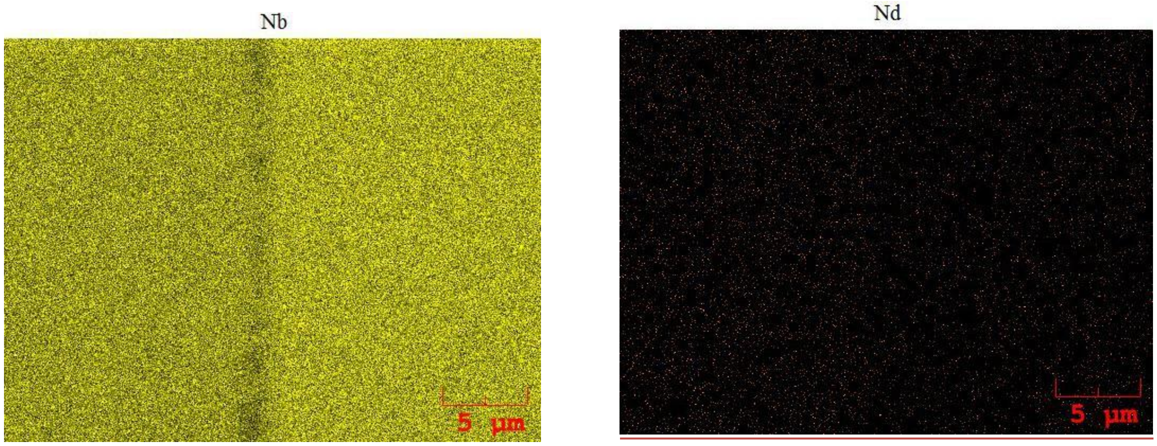


Figure 5. Two-dimensional EDX images of detection of niobium (left) and red bright spots – neodymium (right).

2.3 Optoelectronic Measurements

Figure 6 shows the room temperature probe station arrangement with the chip on the chuck on the probe tips and the fiber input for Halogen lamp illumination. Figures 7–9 show measured current voltage (I-V) characteristics in forward and reverse, with Halogen lamp input demonstrating the impact of optical excitation on the room temperature transport.

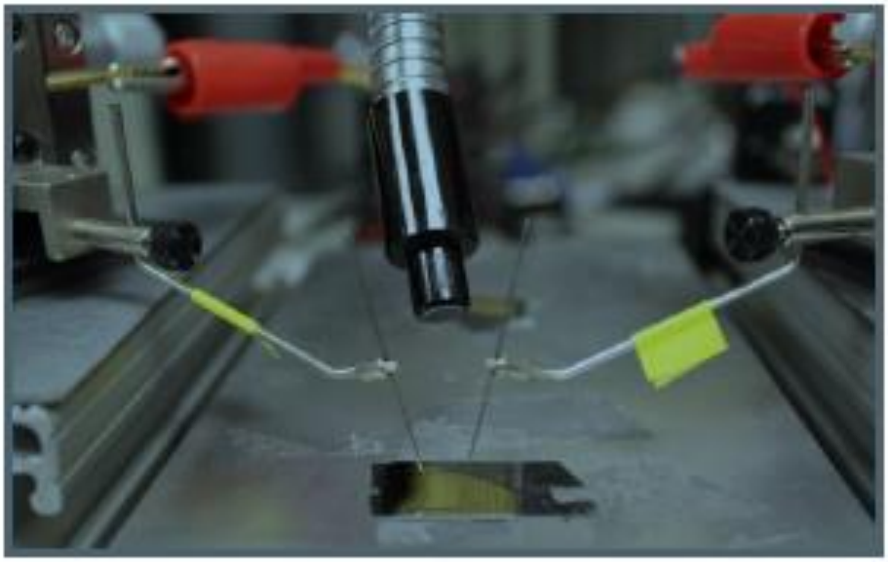


Figure 6. Image of device under test showing electrical probes and fiber input for Halogen lamp and photograph of SSC Pacific mini probe station for room temperature measurements, showing the chip on the sample plate and the electrical probes as well as the optical halogen input.

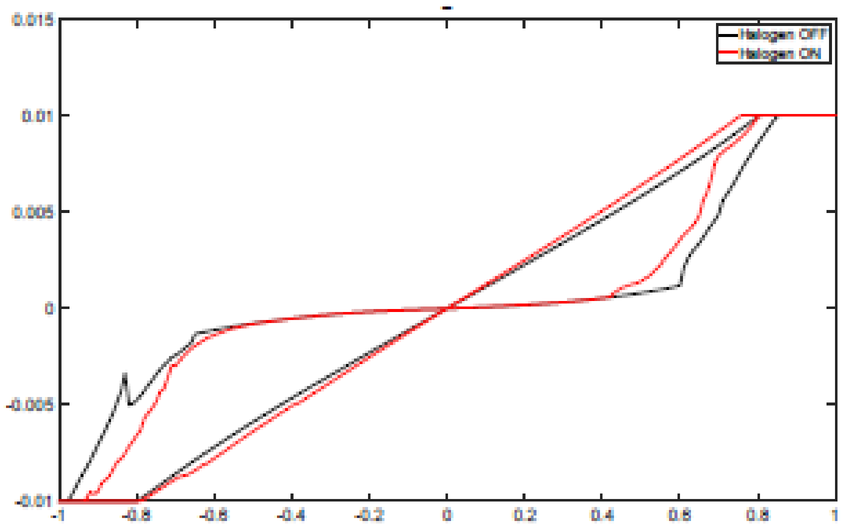


Figure 7. Heterostructure memory hysteresis loops before/after turning on light source. When the halogen light is turned on at low intensity, we see only slight reduction in the memory window, i.e., a reduction in the operational voltage.

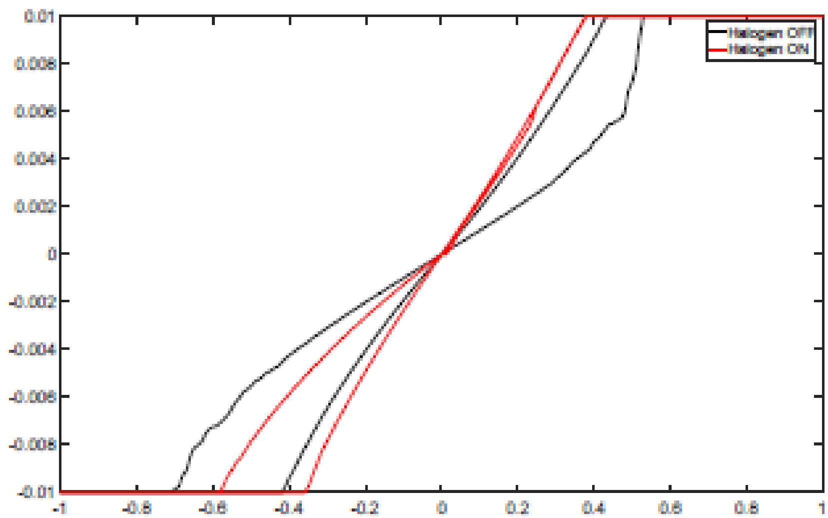


Figure 8. Forward and reverse sweeps without magnetic field. The use of broadband (medium intensity) Halogen illumination clearly modified the transport resulting in a reduced memory window and increase in the asymmetry.

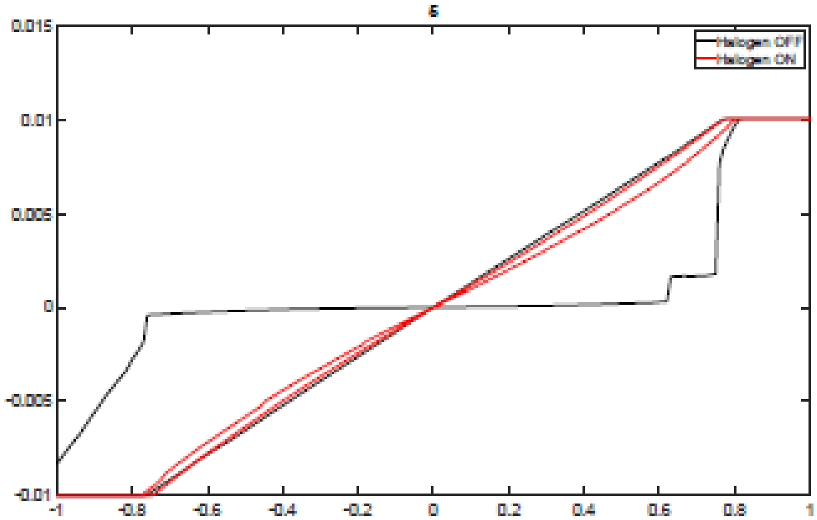


Figure 9. At higher intensity Halogen light input, the memory window almost disappears.

2.4 Magnetic Field Effects

As neodymium is expected to be responsive to magnetic field, we also measured the devices with an applied magnetic field of ~3 milli-Tesla. We find that without illumination, the magnetic field alone results in a significant reduction of the total hysteresis. We experimented with both Halogen and selective optical illumination using an 810-nm LED that is near the expected optical activity of the neodymium. We find the majority of the electronic effect can be observed with the LED alone buttressing the role of the neodymium ions in the optical response, as shown in Figures 10–11.

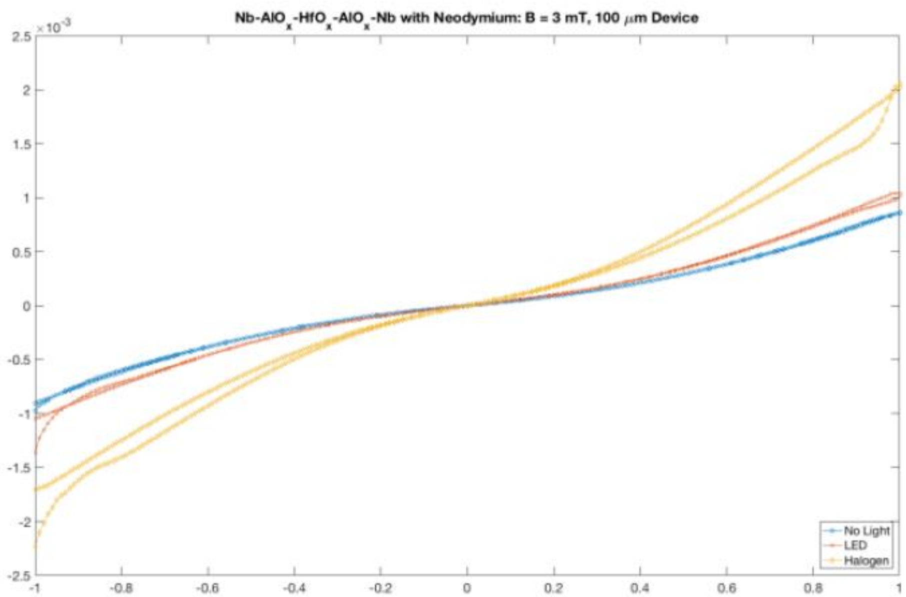


Figure 10. Hysteresis loops under magnetic field (3 mT) with Halogen lamp and comparing with wavelength-selective LED.

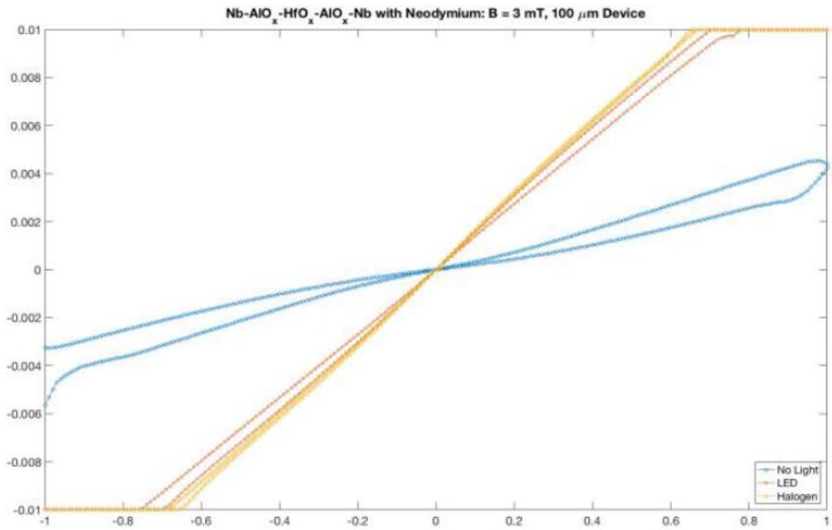


Figure 11. Hysteresis loops under magnetic field with Halogen lamp and comparing with wavelength-selective LED.

3. SUMMARY

In summary, we integrated rare-earth neodymium ions in thin films of niobium and niobium heterostructures. Ions were integrated by implantation with simulations made to extract the profile. EDX spectra confirms a 1 to 3 % composition. We examined niobium heterostructure device response with optical illumination and magnetic field to examine the effects on transport.

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14. ABSTRACT

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15. SUBJECT TERMS
rare-earth ions; quantum memory; optical read-out techniques; optical transmission of qubit states; superconducting quibit design; cryogenic memory implementation; thin films of niobium and niobium-based heterostructure; energy dispersive X-ray spectroscopy; device transport at room temperature;

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